Solar Oscillations in Strong and Weak Fraunhofer Lines Over a Quiet Region

R. KARIYAPPA
Jet Propulsion Laboratory, California Institute of Technology, M/S 169-506, 4800 Oak Grove Drive, Pasadena, CA 91109, U.S.A.

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Address for Correspondence:
R. Kariyappa
Jet Propulsion Laboratory, California Institute of Technology,
M/S 169-506, 4800 Oak Grove Drive, Pasadena, CA 91109
E-mail: rkari@simdac.jpl.nasa.gov
RKariyappa@solar.stanford.edu

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SOLAR OSCILLATIONS IN STRONG AND WEAK FRAUNHOFER LINES OVER A QUIET REGION

R. KARIYAPPA[1]
Jet Propulsion Laboratory, California Institute of Technology, M/S 169-.506, 4800 Oak Grove Drive, Pasadena, CA 91109, U. S. A.

Abstract. We have analysed a 35-rein-long time sequence of spectra in Cal I H-line, NaI D1 and D2-lines, and in a large number of strong and weak Fe] lines taken over a quiet region at the center of the solar disk. The time series of these spectra have been observed simultaneously in these lines under high spatial, spectral, and temporal resolution at the Vacuum Tower Telescope (VTT) of the Sacramento Peak Observatory. We have derived the line profiles and their central intensity values at the sites of the chromospheric bright points, which arc visible in H-line for easy identification. We have done a power spectrum analysis for all the lines using their central intensity values to determine the period of oscillations. It is shown that the 3 FeI lines, present ~23Å away from the core of the H-line representing the pure photospheric lines, NaI D1 and D2 lines, 6 FeI lines at the wings of H-line, and Call H-line exhibit 5-rein, 4,05 -rein, 3,96-rein, and 3.2-min periodicity in their intensity oscillations, respectively. Since all these lines form at different heights in the solar atmosphere from low photosphere to middle chromosphere and show different periodicities in their intensity oscillations, these studies may give an idea about the spatial and temporal relation between the photospheric and chromospheric intensities. Therefore these studies will help to better understand the physical mechanisms of solar oscillations. It is clearly seen that the period of intensity oscillations decreases outwardly from low photosphere

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1 NRC Resident Research Associate, on leave from Indian Institute of Astrophysics, Bangalore 560034, India

to the middle chromosphere, and then to coronal level, which is oscillating with a period of 1-min shown by Pasachoff (1991). Since we have studied single features at a time on the sun (i.e. bright points seen in H-line) in all these spectral lines simultaneously, this may explain about the footprints of the bright points, the origin of 3-rein oscillations, and relation to other oscillations pertaining to these locations on the sun. We have concluded that 80% of the bright points fall in the dark intergranular lanes of the photosphere after carefully examining the brightness (bright threads) extending from the core to the far wings of the II-1ine at the locations of a large number of bright points using their time sequence of spectra.

1. Introduction

Solar oscillations provide a unique method of studying the interior structure of the Sun, however the observed signals convey information integrated over the depth of penetration of the mode studied. Thus low *1* value modes provide data on the deep interior whereas high *1* modes only probe the surface layers. It is from a study of such data that a picture. of the solar interior will emerge. Another penetration depth separation may be obtained by studying different elements in the solar photosphere and chromosphere.

The neutral and singly ionized iron lines have been used to study the photospheric features, and the well known 5-rein oscillations. The CaII H and K resonance lines are used to study the bright magnetic features, and the 3-rein oscillations in the solar chromosphere. Since its discovery by Leighton (1 961), the 5-rein oscillation has been the subject of a large number of observational and theoretical investigations. It has been known since the observations of Jensen and Orrall (1963) that the solar chromosphere oscillates with a period of 180-200s. Observations of time-sequence spectra of CaII H and K lines by Liu (1 974), Cram and Dame

(1 983), Kariyappa, Sivaraman and Anandaram (1 994, henceforth KSA), and Kariyappa (1 994), have shown that the waves with a 3-rein period transport and dissipate a large amount of energy at the sites of the bright points to heat the quiet chromosphere. It is not clearly known about the period of intensity oscillations in other Fraunhofer lines like in NaI D1 and D2 lines, and in strong and weak FeI lines which originate at various levels in the solar atmosphere.

In our previous papers (KSA and Kariyappa, 1994), we have done an extensive analysis on H-1ine profile over a large number of bright points present within the supergranular cell interim-. But in the present paper, we concentrate on the study of intensity oscillations in the NaI D1 and D2 resonance lines, and in a large number of stiong as well as weak Fe] lines both at the far wings and at the wings of the H-1ine for the same locations on the sun which we have studied for the II-line using the time sequence spectra obtained simultaneously. Considering the exceptionally good seeing during the observations and comparing the results of the present analysis with the results of the H-line (KSA), it would be of great interest to establish spatial and temporal relations between the photosphere and chromosphere and this may be considered to explain the physical mechanisms of solar oscillations.

2. Observations and Reduction of the Data

We have used a photographic time sequence of spectra in Nal D1 and D2, and in 9 strong and weak FeI lines observed simultaneously with H-line at the. Vacuum Tower Telescope (VTT) and the echelle spectrograph of the Sacramento Peak Observatory, on September 13, 1971/ and the scheme of observations used here is Program B of the H IRKHAD mode (Beckers et al., 1972) which takes spectra simultaneously in seven line.s along with a large number of Fe] lines at a repetition rate of 12s. The seeing conditions were exceptionally good during the entire duration of 35-min. With 12s for each frame we have, in all, 177 frames. Further details on observations and reduction of the data are given in our earlier papers (KSA, and Kariyappa, 1994). In KSA, we dealt with the analysis of the H-line profile at the locations of 29 bright points (the bright points are designated as B1, B2, B3, ... in Figure 1 of KSA), whereas the present study deals with the analysis of the Nal D1 and D2 at the locations of B1, B2, B3, B5, B8, B1 1, B1 3, and B1 4 and 9 FeI lines at the sites of B2 and B5. The elements, their corresponding wavelengths, the equivalent widths, number of bright points, and total number of line profiles studied in this paper are presented in Table I. We obtained the digital values of the densities for these locations by scanning parallel to the dispersion using a microdensitometer with a scanning aperture of 50μ x 200p which corresponds to 0.004132 Å x 500 km on the sun, We converted the density values first to relative intensity via a photometric calibration and then in terms of the local continuum (White and Suemoto, 1968). We derived the central intensity of each line profile of the D1 and D2, and Fe] lines. We have shown in Figure 1 the time series of H-line parameter, intensity of H_{2V} (KSA). We made plots of central intensity of D1 and D2, and FeI lines versus the time covering the duration of the 35-rein sequence (Figures 2, 3 and 4),

3. **Results and Discussions**

3.1. 1NTENSIT% OSCILLATIONS IN FRAUNHOFER LINES

(u) *CaII II-1ine.* We have studied the time sequence spectra of CaII H-line over a 29 sample of bright points in our previous papers (KSA ; Kariyappa, 1994). It has been shown that these bright points have a period of 190 s in their brightness oscillations. We have shown the light curves of B1, B2, and B5 in Figure 1 (Figure 1 of Kariyappa, 1994) for the entire 35-rein duration of the sequence, to compare with the light cut ves of other Fraunhofer line profiles discussed below. The light curves of the bright points show a strong pulse followed by a number of weaker pulses. We have counted the number of wave pulses for the 35-rein duration and they range from 10 to 12. The strong pulse of each bright point in its light curve is designated as the 'main pulse' and is indicated as PI. Although the main pulse (P1) is easily identifiable from a look at the I_{H2V} versus time curve it may be worth assigning an objective criterion for identifying the main pulse (KSA). The main pulse as well as the follower pulses, although periodic, do not have sinusodial shapes, suggesting a non-linear behaviour. On the other hand, the plots of B1 and B5, would give an impression that one can as well draw curves towards the highest peak showing an exponential growth of the amplitudes and from the highest peak an exponential decay of the amplitudes of the follower pulses. The power spectrum analysis has been done for all the 29 bright points to determine the period of intensity oscillations using the I_{H2V} digital values as discussed in section 3.2.

(b) NaI D1 and D2 lines. We have measured the central intensity of NaI D1 and D2 line profiles at the sites of the bright points B1, B3, B5, B11, B13, and B14 for the entire 35-min time duration. As an example, in Figure 2 we have shown the intensity fluctuations seen at the locations B1, B3, and B5. If we compare Figure 1 with Figure 2, it is seen that the intensity oscillations in the case of II-1ine are very prominent and at the same time they show a clear 3-min period of waves. In the case of NaI D1 and D2 lines (Figure 2) the main pulses are hardly seen during the entire 35-rein duration, but still the intensity oscillations show a periodic fashion. It is difficult to count the number of wave pulses in this case. However, we know that the NaI D1 and D2 lines originate from high photosphere or low chromosphere and hence the bright points are not visible as so intense as in the case of H-line.

(c) FeI lines at the wings of the H-line. We have analysed and derived the central intensity of 6 FeI lines which are present at the wings of the 1 l-line for the two locations namely, B2 and B5 using the time sequence spectra of Call H-line. These lines are blended by H-line and they show intensity oscillations which are highly periodic in their nature similar to H-line intensity oscillations, but with a different period. The wavelengths of these 6 FeI lines are tabulated in Table I. We have plotted the central intensity versus time for the entire 35-rein duration in Figure 3 for the bright point location B2 and in Figure 4 for the bright point location B5 for all the 6 Fe] lines. The FeI 3966.075Å shows three strong wave. pulses with 2-3 smaller wave pulses in between them and the period of the strong pulses is around 3-rein as in the case of H-line (Figure 1). This is because the core of this FeI line forms almost above the level of H-line and hence it shows a chromospheric nature. The wave pulses are quite prominent and we counted the number of pulses and they range from 7 to 8. We have discussed the period of oscillations seen in these lines together with other Franunhofer lines in section 3.2.

(d) Fe] lines far from the wings of the H-line. We have used a time sequence of spectra taken in the continuum region around 3945 Å simultaneously with other lines discussed above to derive the central intensity of 3 Fe] lines (which are -23 Å away from the n-line core on the violet side) at the locations of B2 and B5 and their corresponding wavelengths are tabulated in Table 1. In Figure 5, we have plotted the central intensity of FeI 3945.854Å and Fe] 3945.332A for the locations of both B2 and B5. The intensity oscillation pattern follows the behaviour of H-line over a network elements and they show a 5-7 min periodicity in their intensity oscillations along with small fluctuations (Kariyappa, 1994).

3.2. PER1OD OF OSCILLATIONS AND FOOTPOINTS OF THE BRIGHT POINTS

To determine the period of intensity oscillations, we have done. a power spectrum analysis for all the line profiles using their measured central intensity values for all the locations of the bright points. We have shown the power spectrum plots as an example for the bright point locations B2 and B5 in Figure 6: in (a) for Call H-line, in (b) for NaI D1 line, in (c) for FeI 3967.425Å which is at the wing of H-line, and in (d) for FeI 3945.332Å which is about 23Å away from the H-line. Although there are secondary peaks in some cases, one noteworthy point is that the average period falls in the range of 3.2-rein for Call H-line, 3.96 for the FeI lines which are at the wings of II-1ine, 4.05-min for NaI D1 and D2 lines, and 5-min for FeI lines, present ~23Å away from the H-line core, representing the pure photospheric lines. Pasachoff (1991) has . shown that the corona oscillates with a period of 60 sec using a time sequence spectra in FeX obtained during a total solar eclipse. We have presented the mean period of intensity oscillations for all the lines studied together with FeX line in Table II. As can be seen from Table II, the period of intensity oscillations decreases outwardly from the photosphere (5-rein) to the corona (1-rein). However, further investigations are required to explain the possible physical mechanism for existence of different periods at different heights in the solar atmosphere. It is surmised that the spatial and temporal relations between intensity in the photosphere and chromosphere/corona may probably explain the physical mechanisms of solar oscillations.

Since we have studied the time evolution of individual bright points at a time on the sun in all these above spectral lines (observed simultaneously) which originate at various levels in the solar atmosphere from low photosphere to middle chromosphere from their time sequence spectra, it would be of great interest: (i) to establish the possible existence of one-to-one spatial correspondence of the chromospheric bright points with the photospheric features, and (ii) to explain the physical origin of 3-rein chromospheric oscillations seen in bright points and their relation to other oscillations observed in other spectral lines. In order to establish the footpoints of the CaII H bright points, we have examined the extension of the brightness of the bright points from the core to the far wings on high spatial resolution H-line spectra. We have traced very carefully the brightness of individual bright points, looked at their bright threads (see enlarged photographic print of CaII H-line spectra shown in Figure 1 of KSA) to determine where they will merge with the photospheric continuum, and during this process we find that the bright threads, originating from the bright points, merge with the dark threads representing the dark intergranular regions. This procedure has been repeated for 70-80 bright points to increase our statistical accuracy. We find from this study that the 80% of the bright points fall in the dark intergranular lanes of the photosphere. A similar investigation has been carried out independently by Bagare (1992, private communication) for a large number of bright points and he also arrived with the same number.

4. Conclusions

We have used very high quality time sequence spectra obtained simultaneously in CaII H-line, NaI D1 and D2 lines, and 9 FeI lines with a spatial resolution of 1 arc sec or better to study the intensity oscillations at the locations of large sample of bright points, seen in chromospheric level in H-line. It is known that all these lines form at various levels in the solar atmosphere, from low photosphere to middle chromosphere and we have studied single feature at a time on the sun observed simultaneously in all these spectral lines for a large number of bright points. The main conclusions that have emerged from this study are:

i. The Fe] lines, present ~23Å away from the wings of the H-line, representing the pure photospheric lines, show a periodicity of well known 5-rein oscillations in their central intensity.

ii. The Nal D1 and D2 lines are associated with 4.05-min periodicity at the same locations of the bright points,

iii. The Fe] lines, present at the wings of the H-line, show a periodicity of 3.96-rein in their central intensity.

iv. The Call H-line shows a 3-rein periodicity in their intensity oscillations at the locations of bright points.

v. Being/all these spectral lines are forming at different heights in the solar atmosphere, and showing the period of intensity oscillations decreases outwardly from the photosphere (5-rein) to the corona (1 -rein), it is surmised that the spatial and temporal relations between intensity in the photosphere and chromosphere/corona may enabled to explain the physical mechanisms of solar oscillations. However, further investigations are required to explain the possible physical mechanism for existence of different periods at different heights in the solar atmosphere.

vi. By examining a large number of bright threads at the locations of the bright points extending right from the core to the far wings of the H-line on the time sequence spectra, we concluded that the 80% of the bright points seen at the chromospheric level fall in the dark intergranular lanes of the photosphere.

Acknowledgements

I thank Drs J. M. Beckers, Raymond Smartt and K. R. Sivaraman for use of the HIRKHAD data. A pat-t of this work was carried out while 1 was holding a National Research Council-NASA Research Associateship at the Jet Propulsion Laboratory, California Institute of Technology. My thanks are also due to Drs M. Neugebauer and J. M. Pap for going through the manuscript and for their useful comments and suggestions.

References

Beckers, J. M., Master, H. A., Mann, G. R., and Brown, D. R.:1972, *Solar Phys. 25, 81,*

Cram, L. E. and Dame, L.: 1983, *Astrophys. J. 272, 355.*

Jensen, E. and Orrall, F. Q.:1963, *Astrophys. J. 13S, 252.*

Kariyappa, R., Sivaraman, K. R. and Anandaram, M. N.:1994, *Solar Phys.* **151, 243** (KSA).

Kari yappa, R.:1994, *Solar Phys.* **154,** 19.

Leighton, R. B.: 1961, in R. N. Thomas (cd.), *'Aerodynamic Phenomena in Stellar Atmospheres', IA U Symp.* **12,** 321.

Liu, S. Y.:1974, *Astrophys. J.* **189,** 359.

Pasachoff, J. M.: 1991, in P. Ulmschneider, E. R. Priest, and R. Rosner (eds.), *'Mechanism of Chromospheric and Coronal Heating',* p.121.

White, O. R. and Suemoto, Z.:1968, *Solar Phys. 3, 523.*

TABLE 1

Elements, wavelengths, equivalent widths, number of bright points studied and total number of line profiles

Element	Wavelength (Å)	Equivalent Width (Å)	Number of Bright Points choosen for study	Total number of line profiles
CaII H	3968.492	14.40	29	5133 (KSA)
NaI D1	5895.940	0.57	7	1239
NaI D2	5890.973	0.77	7	1239
FeI	3967.425	0.19	2	354
FeI	3966.825	0.11	2	354
FeI	3966.500	0.35	2	354
FeI	3966.075	0.66	2	354
FeI	3965.930	0.25	2	354
FeI	3965.525	0.20	2	354
FeI	3945,854	0.81	2	354
FeI	3945.332	0.68	2	354
FeI	3945.127	0.79	2	354

TABLE 11

Mean period in intensity oscillations in strong and weak fraunhofer lines

Line	Mean Period (minute)
FeX	1.00 (Pasachoff, 1991)
Call H	3.02 (KSA)
FeI lines at the wing of H-line	3.96
NaI D1 & D2	4.05
Fe] lines away from the wing of H-line	*5.00*

Figure Captions

Fig. 1. The variations in intensity of the H_{2V} emission peak (I_{H2V}) of the three bright points (BI, B2, and B5) during the 35-rein observations. The main pulse designated as P1 is 4 to 5 times the normal brightness value and is followed by several pulses with decreasing amplitudes (Kariyappa, 1994).

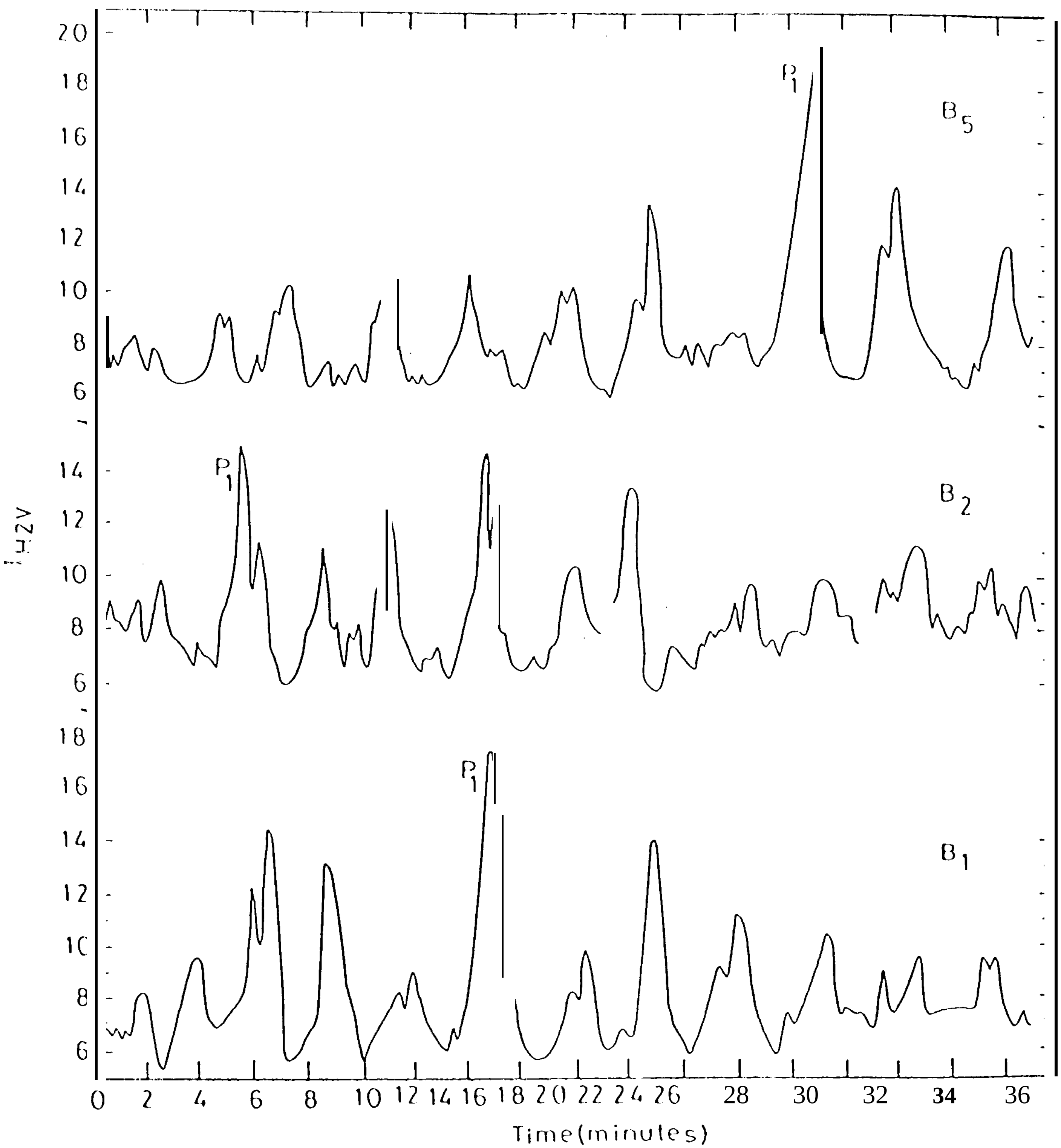
Fig. 2. The variations in central intensity of NaI D1 and D2 lines at the three locations: (a) Bl, (b) B3, and (c) B5, during the 35-rein observations.

Fig. 3. The variations in central intensity at the location of B2 in Fe] lines at the wings of the H-line: (a) λ3967.425Å, (b) λ3966.825Å, (c) λ3966.50Å, (d) λ3966.075Å, (e) λ3965.930Å, and (f) λ3965.525Å.

Fig. 4. The variations in central intensity at the location of B5 in FeI lines at the wings of the H-line: (a) λ3967.425Å, (b) λ3966.825Å, (c) λ3966.50Å, (d) λ3966.075Å, (e) λ3965.930Å, and (f) λ3965.525Å.

Fig. 5. The variations in central intensity of two Fe] lines which are. present ~23Å away from the core of the H-1ine: Fe] λ3945.854Å at the locations of (a) B5 and (b) B2 ; FeI λ3945.332Å at the locations of (c) B5 and (d) B2.

Fig. 6. Sample of power spectrum of (a) CaII II-line at the location of B1, (b) Nal D1 at the location of B1, (c) Fe] λ3967.425Å at the wing of H-line at the location of B5, and (d) FeI λ3945.332Å which is ~23Å away from the core of the II-1ine at the location of B5.



B5
B2
B1
P1
P1
P1
I_{H_2V}
20
18
16
14
12
10
8
6
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36
Time(minutes)

Fig. 1

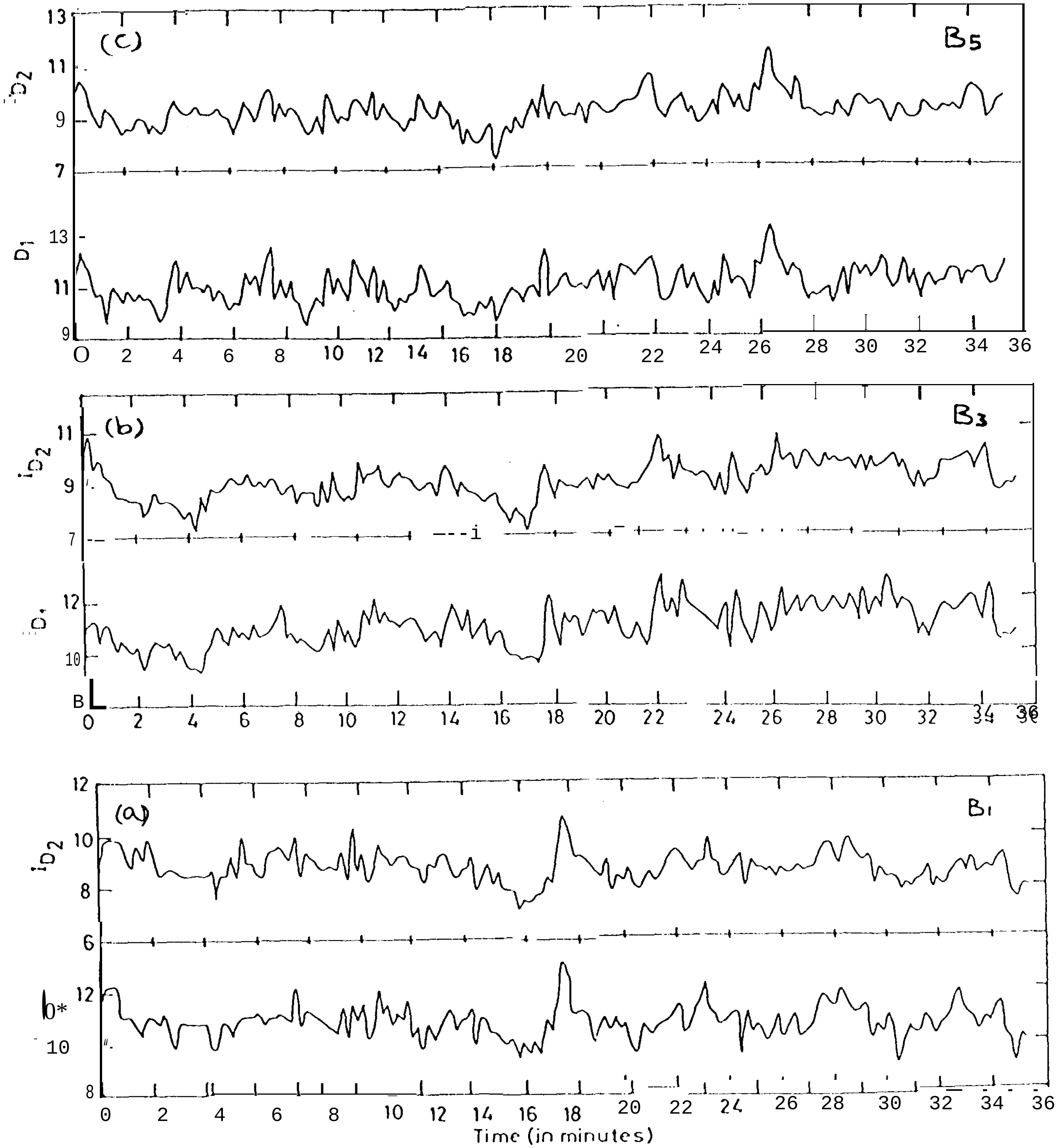
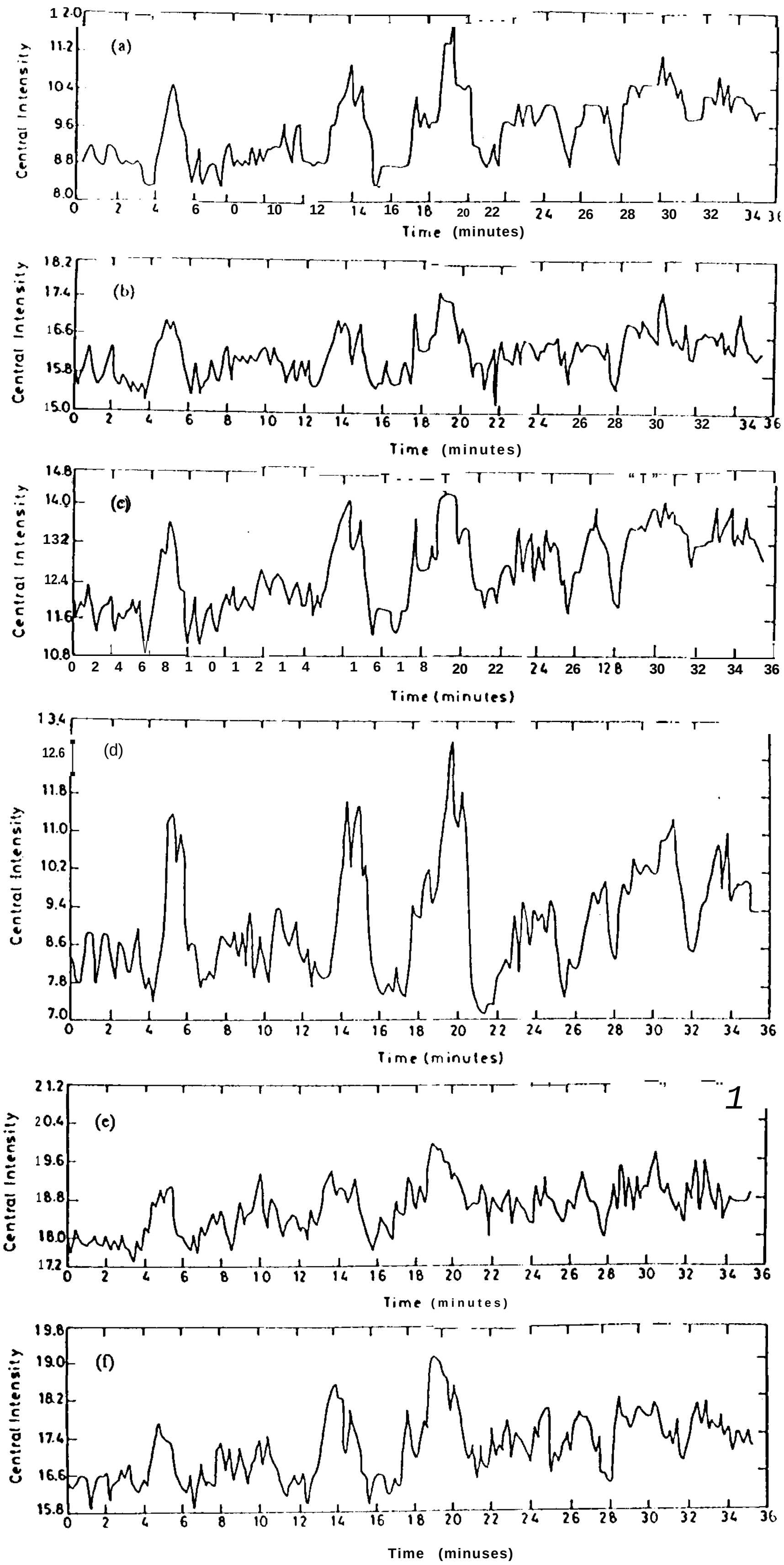


fig. 2



(a)
Central Intensity
Time (minutes)
(b)
Central Intensity
Time (minutes)
(c)
Central Intensity
Time (minutes)
(d)
Central Intensity
Time (minutes)
(e)
Central Intensity
Time (minutes)
(f)
Central Intensity
Time (minuses)

Fig. 3

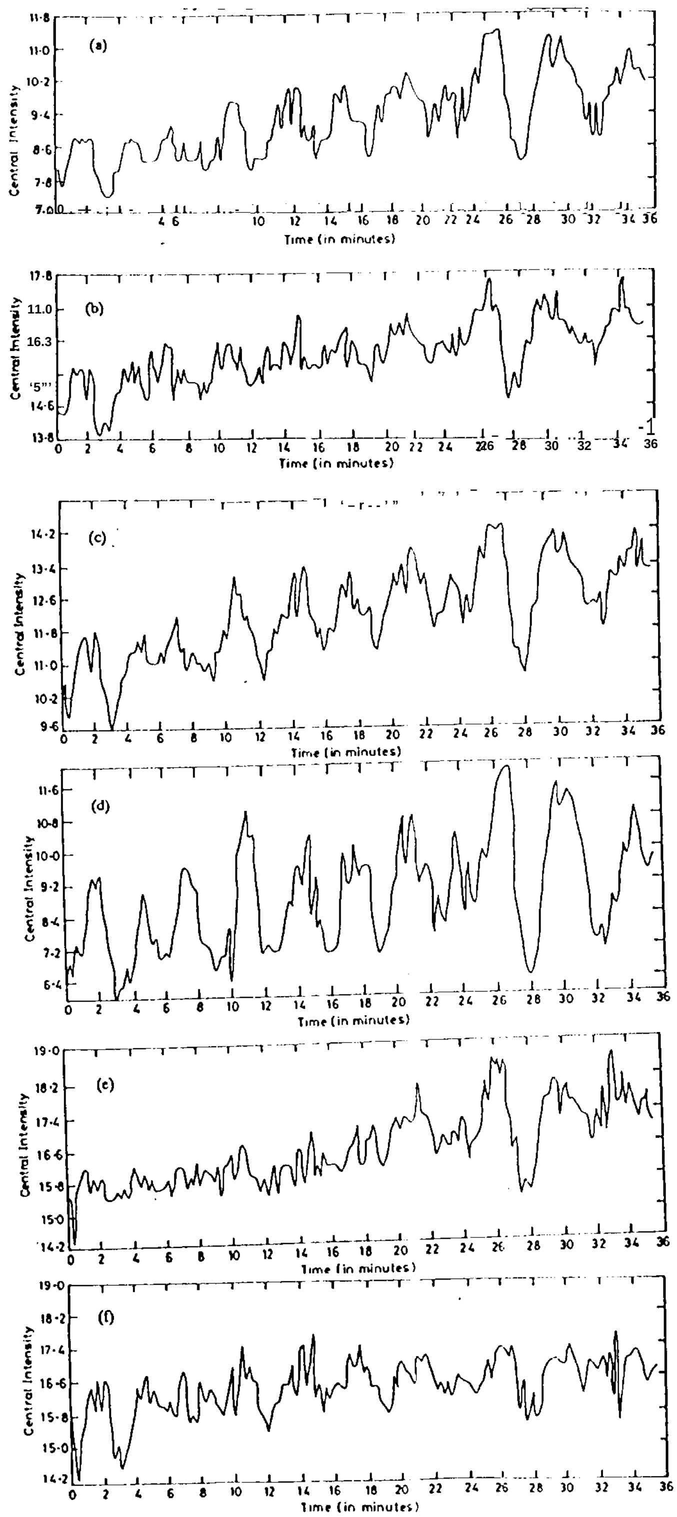


Fig. 4

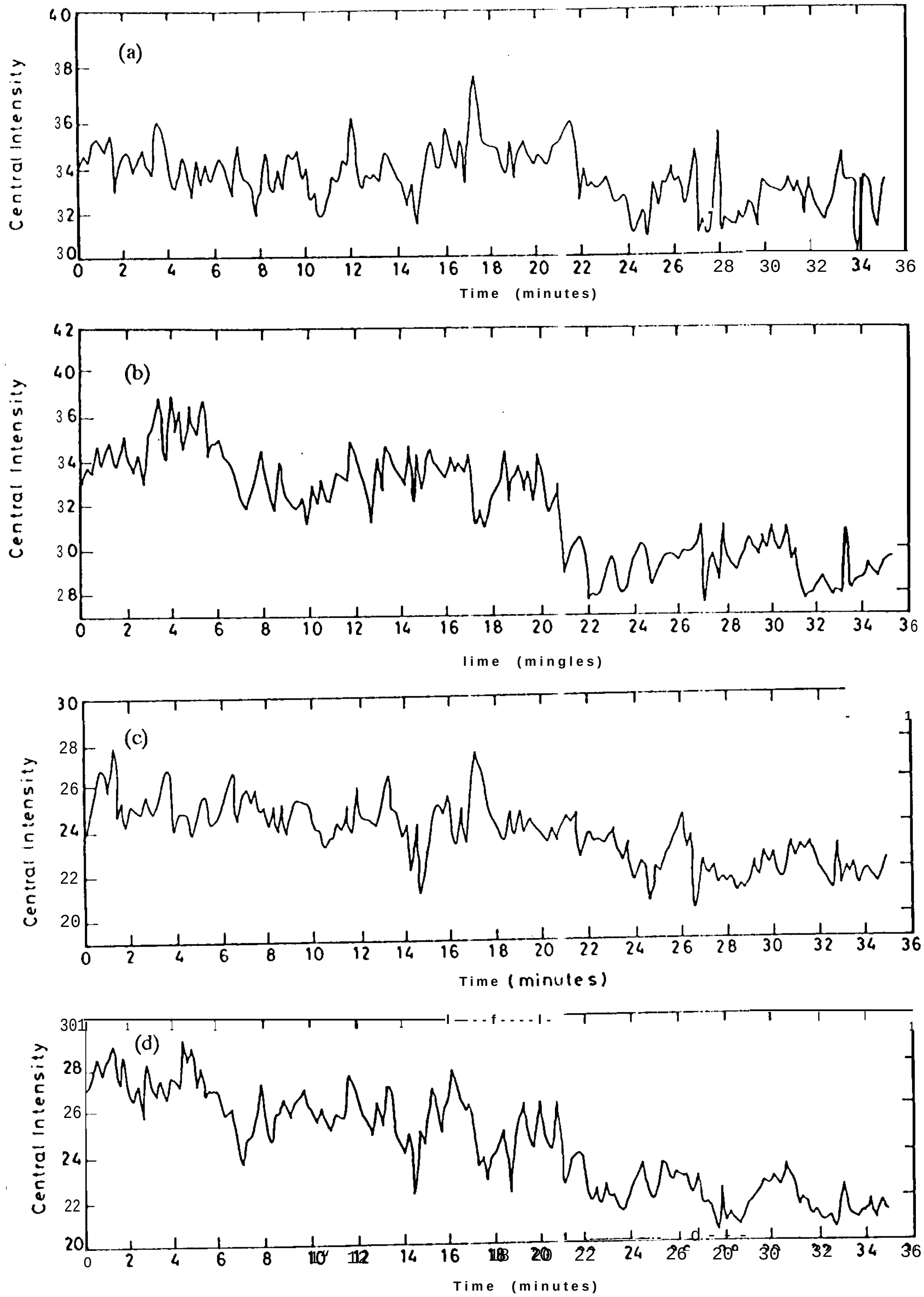

(a)
Central Intensity
Time (minutes)
(b)
Central Intensity
lime (mingles)
(c)
Central Intensity
Time (minutes)
(d)
Central Intensity
Time (minutes)

Fig. 5

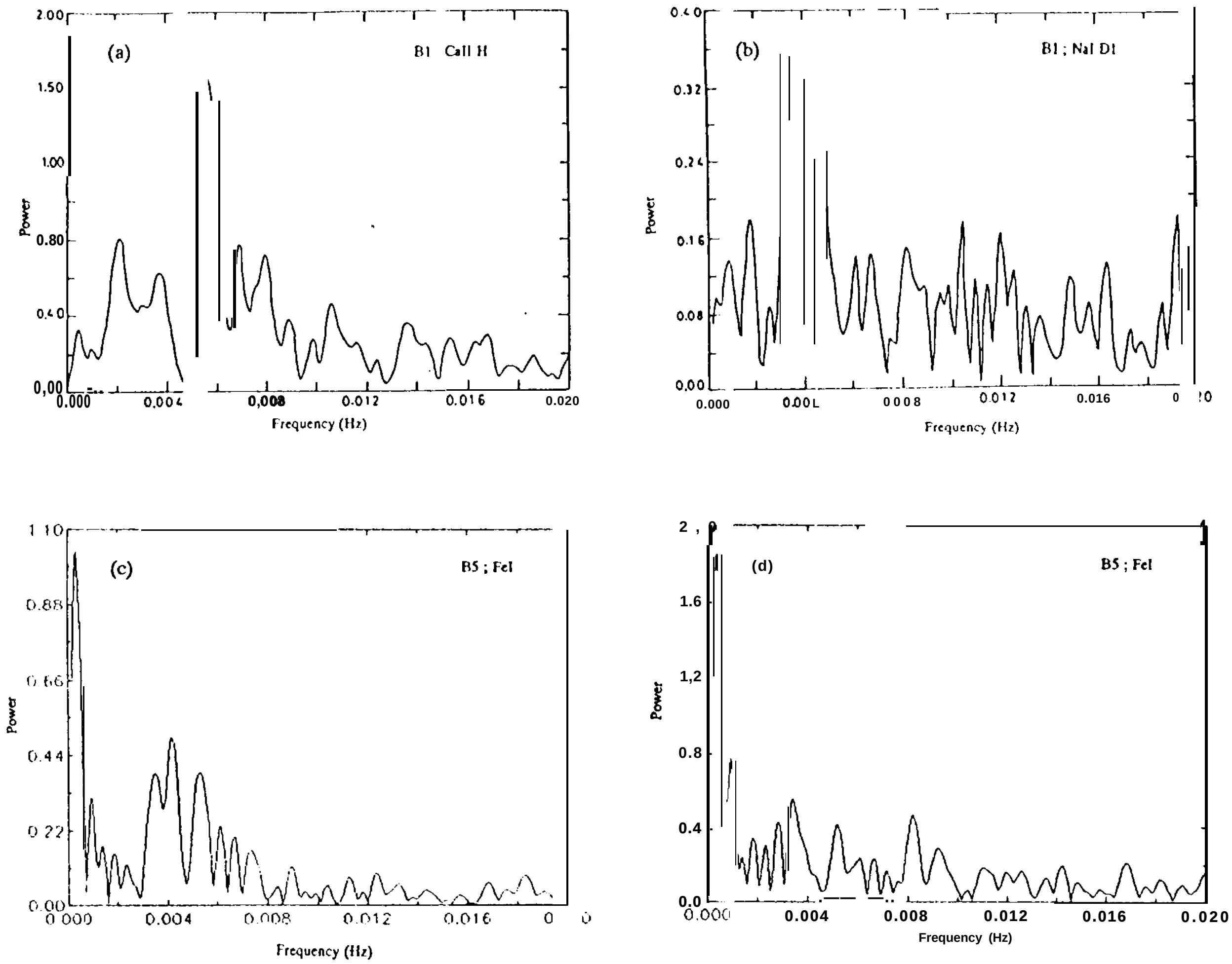


Fig. 6